Optical variability of the ultraluminous X-ray source NGC 1313 X-2

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We analyzed the longest phase-connected photometric dataset available for NGC 1313 X-2, looking for the ∼6 day modulation reported by Liu et al. (2009). The folded B band light curve shows a 6 days periodicity with a significance slightly larger than 3σ. The low statistical significance of this modulation, along with the lack of detection in the V band, make its identification uncertain.

1 Introduction

NGC 1313 X-2 is located in the outskirts of the barred spiral galaxy NGC 1313 at a distance of 3.7-4.27 Mpc (Tully 1988; Méndez et al. 2002; Rizzi et al. 2007). Its observed X-ray luminosity varies between a few $\times 10^{39}$ erg/s and $\sim 10^{40}$ erg/s in the 0.3-10 keV band (Feng & Kaaret 2006). The source has been extensively studied in the X-ray and optical bands (e.g. Mucciarelli et al. 2007; Grisé et al. 2008). It belongs to a handful of ultraluminous X-ray sources (ULXs) clearly associated to stellar optical counterparts (e.g. Liu et al. 2004; Kaaret et al. 2004; Mucciarelli et al. 2005; Soria et al. 2005). These sources appear almost ubiquitously hosted in young stellar environments (e.g. Pakull et al. 2006, Ramsey et al 2006, Liu et al. 2007) and have properties consistent with those of young, massive stars. However, some ULXs appear to be associated to older stellar populations and one possible later type stellar counterpart is now known (Feng & Kaaret 2008; Roberts, Levan & Goad 2008), although its spectral classification may be affected by significant galactic and extra-galactic reddening (Grisé et al. 2006). In the case of NGC 1313 X-2, a single optical counterpart has been identified through a chain of efforts (Zampieri et al. 2004; Mucciarelli et al. 2005, 2007; Pakull et al. 2006; Liu et al. 2007; Grisé et al. 2008). This star has an extinction-corrected absolute magnitude $M_B \sim -4.5$ mag and colors $(B-V)_0 \sim -0.15$ mag and $(V-I)_0 \sim -0.16$ mag (Mucciarelli et al. 2007; Grisé et al. 2008), consistent with a B spectral type.

Liu et al. (2009) found a possible periodicity of 6.12± 0.16 days in the B band light curve of the optical counterpart of NGC 1313 X-2, that was interpreted as the orbital period of the binary system. Three cycles were detected in

Table 1 Log of the VLT+FORS1 and HST+WFPC2 photometric observations of NGC 1313 X-2

Obs.	Date	MJD	Exposure (s)	Instr.
1	2007-10-21	54394.362587	242×2	FORS1
2	2007-11-15	54419.220472	242×2	FORS1
3	2007-11-15	54419.277624	242×2	FORS1
4	2007-11-16	54420.255469	242×2	FORS1
5	2007-12-06	54440.075805	242×2	FORS1
6	2007-12-10	54444.173203	242×2	FORS1
7	2007-12-14	54448.121299	242×2	FORS1
8	2008-01-31	54496.073081	242×2	FORS1
9	2008-03-02	54527.059338	242×2	FORS1
10	2008-03-05	54530.053776	242×2	FORS1
11	2008-03-08	54533.056052	242×2	FORS1
12	2008-05-21	54607.911122	500×2	WFPC2
13	2008-05-22	54608.043761	500×2	WFPC2
14	2008-05-23	54609.042372	500×2	WFPC2
15	2008-05-24	54610.040983	500×2	WFPC2
16	2008-05-25	54611.038900	500×2	WFPC2
17	2008-05-26	54612.104178	500×2	WFPC2
18	2008-05-27	54613.179178	500×2	WFPC2
19	2008-05-28	54614.178483	500×2	WFPC2
20	2008-05-29	54615.177789	500×2	WFPC2
21	2008-05-30	54616.097233	500×2	WFPC2
22	2008-05-31	54617.109039	500×2	WFPC2
23	2008-06-01	54618.692372	500×2	WFPC2
24	2008-06-02	54619.173622	500×2	WFPC2
25	2008-06-03	54620.105567	500×2	WFPC2
26	2008-06-04	54621.171539	500×2	WFPC2
27	2008-06-05	54622.104178	500×2	WFPC2
28	2008-06-06	54623.102789	500×2	WFPC2
29	2008-06-07	54624.034733	500×2	WFPC2
30	2008-06-08	54625.100706	500×2	WFPC2
31	2008-06-09	54626.611817	500×2	WFPC2

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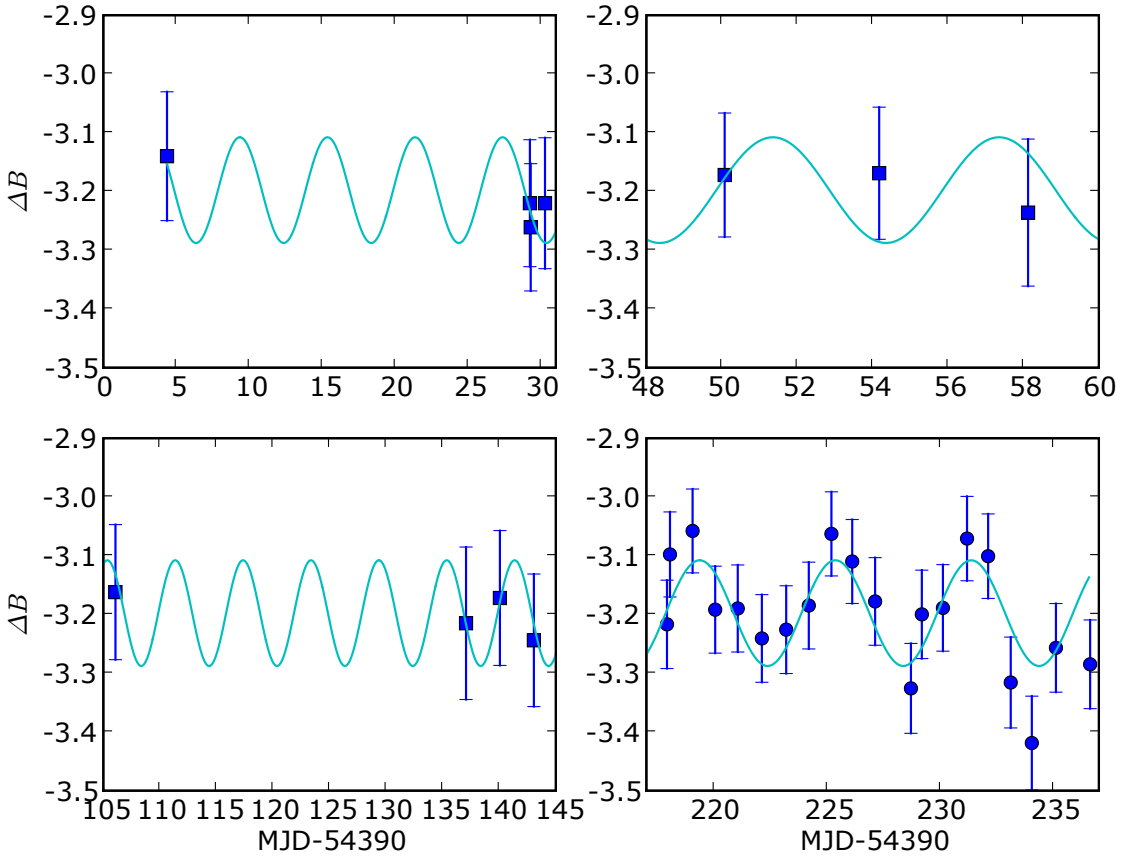

Fig. 1 Joint VLT+HST light curve of NGC 1313 X-2 in the B band. The squares are the VLT+FORS1 data, while the circles represent the HST+WFPC2 observations. The magnitudes are the difference with those of a reference field star. The data cover a period of ~ 7.5 months. The solid (*cyan*) line is the best fitting sinusoid with a period $P = 6.0$ days.

the B band, while no modulation was found in V. Previous studies carried out on the available HST and VLT observations led to negative results (Grisé et al. 2008). More recently, lack of significant photometric variability on a new sequence of VLT observations has been reported by Grisé et al. (2009).

Here we present a preliminary reanalysis of the joint VLT+FORS1 and HST+WFPC2 photometric observations of NGC 1313 X-2 obtained during the years 2007-2008, with the aim of clarifying the statistical significance of the orbital periodicity identified by Liu et al. (2009). Further details will be reported in a separate paper (Zampieri et al., in preparation).

2 VLT and HST observations

NGC 1313 X-2 was observed with VLT+FORS1 between October 2007 and March 2008 (11 epochs; Grisé et al. 2009) and with HST+WFPC2 between May and June 2008 (20 epochs; Liu et al. 2009). The quality of the HST images is fair, despite the degradation of the central PC chip. A log of the observations is reported in Table 1. We re-analyzed the whole dataset in a homogeneous way, looking for the $\sim$6 day periodicity reported by Liu et al. (2009).

After performing standard image reduction in the IRAF environment, the two exposures taken a few minutes apart each night were combined together and cleaned for cosmic rays. To accurately photometer the objects, we used AIDA (Astronomical Image Decomposition and Analysis; Uslenghi & Falomo 2008), an IDL-based package originally designed to perform two-dimensional PSF model fitting of quasar images. For the analysis of the WFPC2 exposures, we loaded into AIDA the appropriate PSF simulated with Tiny Tim v. 6.3[1].

Analyzing VLT and HST measurements together requires attention to be paid to the systematic differences between the two photometric systems. We then first converted the HST instrumental magnitudes to the standard $UBVRI$ photometric system using the updated transformation equations and coefficients published in Dolphin (2009) for the appro-

[1] http://www.stsci.edu/software/tinytim/tinytim.html

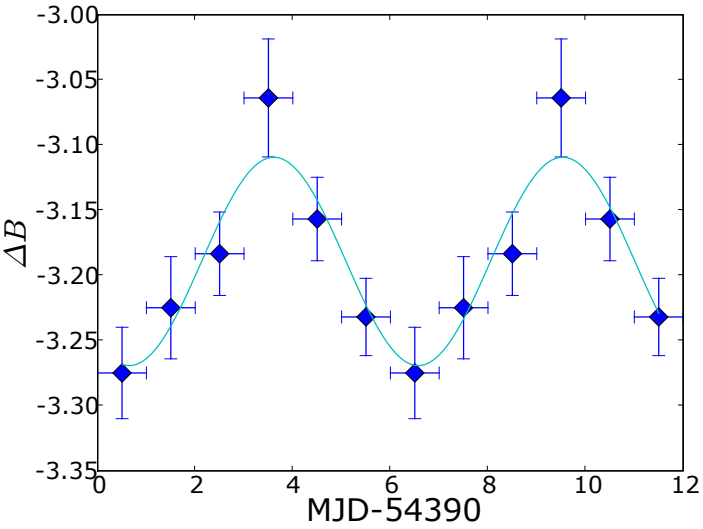

Fig. 2 Binned light curve (6 bins) of the B band VLT+HST dataset of NGC 1313 X-2, folded over the best estimate of the period. The best fitting sinusoid is also shown.

priate instrumental gain (which is equal to 7 in our case)[2]. The color correction term was computed adopting the $(B-V)$ color reported in Mucciarelli et al. (2005). In spite of this, residual systematic differences between the two photometric systems might still be present and affect our measurements. In particular the color correction term is sensitive to the overall bandpass (telescope plus atmospheric response) of the instruments. Further attention should be paid to minimize the effects of possible absolute calibration uncertainties. We then decided to perform differential photometry of the target with respect to a nearby field star (star D in Zampieri et al. 2004), located on the same chip in both instruments. The reference star is brighter than the target and has a low root mean square variability (~ 0.05 mag in the VLT and $\lesssim 0.02$ mag in the HST exposures). For similar reasons, during all the observations performed with HST+WFPC2, the field was always oriented in the same direction and the target and reference star were always located on the same position on the central PC chip.

Figure 1 shows the B band light curve of NGC 1313 X-2 obtained in this way. The data show clear short term (~ 1 day) variability, likely due to X-ray irradiation. As can be seen from Figure 1, the VLT data have much smaller root mean square variability ($\sim$0.04 mag) than the HST ones ($\sim$0.09 mag). Thus, there are different levels of optical activity whose origin is unclear and is under investigation at present (Zampieri et al., in preparation). Superimposed on the short term stochastic variability, the HST dataset shows also an approximately sinusoidal modulation with a period of 6 days (Figure 1).

[2] http://purcell.as.arizona.edu/wfpc2_calib/

3 Results

Following Liu et al. (2009), we fitted all the VLT+HST datasets (31 epochs) with a sinusoid:

$$\Delta B = \bar{B} + A\sin(2\pi(t-t_1)/P+\phi)\,, \qquad (1)$$

where A, P and ϕ are the amplitude, period and phase, respectively, $t_1 = 54390$ is a reference epoch and $\bar{B} = <\Delta B>=<B_D - B_{target}>= -3.198$ is the average differential magnitude. The best fitting parameters are: $P = 6.01^{+0.17}_{-0.01}$ days, $A = 0.09^{+0.02}_{-0.02}$ mag, $\phi = 94^{0+13^0}_{-13^0}$. The value of the amplitude and period are in agreement with those reported by Liu et al. (2009). The error on the period is such that $\Delta P(T/P) \lesssim 6$ days, where $T \sim 200$ days is the interval between the first and last observation (sampling interval). This is not larger than P, indicating that the two datasets can be phase connected. Although the VLT data alone do not show evidence of periodicity, they appear to be consistent with the sinusoidal modulation observed in the HST observations. A comparison of the VLT data alone with the best fit from the HST data shows that the former are statistically consistent with the HST fit (reduced chi-square $\chi^2_r = 0.42$).

We reanalyzed also the V band HST+WFPC2 images and found no significant periodic variability. If the observed modulation is caused mostly by X-ray irradiation, the amplitude in the V band is expected to be smaller than that in the B band (Patruno & Zampieri 2010). A sinusoidal modulation with the same period and phase obtained from the fit of the B band data and an amplitude $\lesssim 0.04$ mag is consistent, within the errors, with the data (reduced chi-square $\chi^2 \lesssim 1.3$).

The statistical significance of the B band modulation was tested performing a Lomb-Scargle periodogram analysis of all the observations. We found that the modulation

is significant only at the $\lesssim 1.5\sigma$ level. Binning the light curve in 6 bin intervals and performing an epoch folding period search, the 6 days modulation is recovered with a significance slightly larger than 3σ (see Figure 2). Although the binned light curve suggests that the periodicity may be there, the low statistical significance of the B band modulation, along with the lack of detection in the V band, make its identification uncertain. A dedicated photometric monitoring campaign under homogeneous observing conditions to minimize systematic uncertainties are needed to confirm it.

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